TECHNICAL REPORT

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INFRARED ALGORITHM DEVELOPMENT FOR OCEAN OBSERVATIONS WITH EOS/MODIS

Abstract

Efforts continue under this contract to develop algorithms for the computation of sea surface temperature (SST) from MODIS infrared retrievals. This effort includes radiative transfer modeling, comparison of *in situ* and satellite observations, development and evaluation of processing and networking methodologies for algorithm computation and data accession, evaluation of surface validation approaches for IR radiances, and participation in MODIS (project) related activities. Efforts in this contract period have focused on radiative transfer modeling, evaluation of atmospheric correction methodologies, involvement in field studies, production and evaluation of new computer networking strategies, and objective analysis approaches.

MODIS INFRARED ALGORITHM DEVELOPMENT

A. Near Term Objectives

A.1. Continue algorithmic development efforts based on experimental match-up databases and radiative transfer models.

A.2. Continue interaction with the MODIS Instrument Team through meetings and electronic communications.

A.3 Continue evaluation of different approaches for global SST data assimilation and work on statistically based objective analysis approaches.

A.4 Continue evaluation of high-speed network interconnection technologies.

A.5 Continue evaluation of various *in situ* validation approaches for the MODIS IR bands.

A.6 Provide investigator and staff support for the preceding items.

B. Overview of Current Progress

B.1 January-June 1996

Activities during the past six months have continued on the previously initiated tasks. There have been specific continuing efforts in the areas of (a) radiative transfer modeling, (b) generation of model based retrieval algorithms, (c) continued work on IR calibration/validation as part of the MODIS Ocean Science Team cruise effort, and (e) work on test and evaluation of an experimental wide area network based on ATM technology. Previously initiated activities such as team related activities are ongoing.

Special foci during this six month period have been:

1) continue exploring sources of radiosondes to compile a global marine data set that correctly represents the distributions of conditions in the atmosphere,
2) AVHRR *in situ* comparison data base studies.
3) participate in the DOE/NOAA/NASA ARM Combined Sensor Project cruise in the Tropical Western Pacific in the spring of 1996,
4) Construction of a marine FTIR instrument for cal/val applications by UWSSEC via subcontract .

B.1.1 Radiative Transfer Modeling

Dr. Richard Sikorski has been working on the radiative transfer code that calculates spectra of the infrared radiation emerging from the atmosphere at satellite height. It includes components from the atmosphere, both downwelling radiation reflected at the sea surface and upwelling radiation, and from the sea-surface. A large data base of pre-computed radiative parameters of the relevant gases is stored for a range of pressures and temperatures, and realistic atmospheric profiles are provided by marine radiosoundings. Other variables required by the model are the properties of atmospheric aerosols and the SST. To derive simulated channel brightness temperatures of the satellite radiometers, the channel spectral responses must be well known, and to generate atmospheric correction algorithms the noise characteristics of the channels must be well described. This model was developed at the Rutherford Appleton Laboratory in the UK and has been used successfully to derive atmospheric correction algorithms for the AVHRR and the ATSR. The pre-launch algorithms for the ATSR have subsequently been found to be accurate.

To generate algorithms applicable to global MODIS retrievals it is important to use a input parameters (e.g. radiosondes, aerosols etc.) that truly represent the environmental variability, and significant effort is being invested in generating a definitive set of marine radiosondes from various archives. In addition, tropospheric aerosols are generally not routinely measured but they can be parameterized in terms of horizontal visible range, and the holdings of the National Climatic Data Center have been analyzed to determine the mean value (22.5 km) of horizontal visible range. Seasonal and regional variations will be further investigated. The model has been ported to UNIX machines and rewritten to reduce it's machine dependence.

The latitudinal and seasonal variations of AVHRR and MODIS brightness temperatures are currently being investigated, and the model is being used to determine the consequences of inadequacies in the knowledge of the MODIS infrared channel spectral response functions.

B.1.2 Algorithm Development Efforts Based on Experimental Match-up Data bases

During this period we continued the compilation of in situ sea surface temperature (SST) data from moored and drifting buoys in order to build a co-temporal, co-located set of in situ and AVHRR data. The "matchups" are being used to estimate SST algorithm coefficients and to characterize algorithm performance. We have completed the production of 1994 matchups for NOAA-11. This gives us a complete database of matchups for the entire lifetime of the AVHRR aboard NOAA-11 (November 1988 to September 1994).

We have also completed matchups for the NOAA-9 transition period after the demise of NOAA-11 (September 1994 to February 1995) and for the first part of the NOAA-14 record (February-December 1995).

Beginning with the 1994 NOAA-11 matchups, we incorporated a new source of in situ SST data: moored buoys in the northeast Atlantic operated by the United Kingdom's Meteorological Office. These buoys provide much-needed data in high-latitude regimes, as the matchups are dominated by data from tropical and temperate regions. Also, a previously unavailable set of drifting buoy data for the Greenland-Iceland region has been obtained from NATO, and will be used in future matchup data bases.

We have experimented with numerous alternative formulations for an AVHRR SST algorithm. In close collaboration with the SST Science Working Group, we have defined a consensus algorithm. The algorithm is based on the non-linear SST formulation (NLSST) originally proposed by C. Walton (NOAA-NESDIS). In order to minimize temporal trends detected in the residuals (defined as in situ minus satellite SST), the algorithm coefficients are estimated on a monthly basis, using matchups for a 5-month window centered on the month for which coefficients are being estimated. The performance of the algorithm is being assessed in relation to reference fields such as the Reynolds Optimally Interpolated (OI) fields. Results suggest that, in some regions, there may be errors in the retrievals associated with atmospheric aerosols. Examples of this are the eastern tropical Atlantic and the northern Indian Ocean.

Until now, the compilation of in situ SST data to be used in developing the matchups has been based on historical data from archive centers (e.g., the National Oceanographic Data Center). In the last few months, we have initiated a collaboration with the Naval Oceanographic Office (NAVOCEANO/NRL) to access in situ measurements in a more timely manner. They are providing electronic access (FTP of the records to our facility) to the in situ data they are collecting. At present, a substantial amount of effort is being dedicated to developing the procedures for the quality control of the data and to producing input to the matchup process. We are implementing these procedures and hope to be able to produce an interim set of retrieval coefficients with a three month delay.

B.1.3 The Combined Sensor Cruise of the NOAA ship Discoverer

Dr. Peter Minnett participated in the Combined Sensor Cruise of the NOAA ship *Discoverer* in the Tropical Western Pacific Ocean from mid-March to mid-April. He was accompanied by Dr. R Knuteson and Mr. J Short, and two students, from the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison.

The *Discoverer* sailed from Pago-Pago in American Samoa on Thursday, 14 March, 1996, and headed northwest to a point at 2°S, 180°W where the cruise track turned due west until a point was reached about 100 km off the island of Manus, Papua New Guinea (Figure 1). The following ten days were spent occupying five, two day stations at varying distances from the island. The ship returned along a line at ~1°S to the date line, and then headed northeast to arrive at Honolulu on Saturday, 13 April.

One of the objectives of this cruise was to test the use of the prototype Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), which will be a key instrument in the post-launch validation of the infrared channels of MODIS, and of the derived Sea-Surface temperature (SST) corrected for the effects of the intervening atmosphere. The area of the cruise included the "warm-pool" of the tropical Pacific where both the SST and the atmospheric water-vapor loading exhibit global maxima. Thus the cruise conditions are at a climatological extreme. The high air temperatures and strong insolation also meant that the instruments were being stressed towards their upper operating temperatures.

The M-AERI is a Fourier-Transform Interferometric Radiometer (FTIR) operating in the infrared wavelength range of ~3 to ~18μm and measures spectra with a spectral resolution of ~0.5

cm^{-1}. It uses a sandwich of two infrared detectors (Indium Antimonide and Mercury Cadmium Telluride) to achieve the wide spectral range, and these are cooled to 77K by a liquid nitrogen dewar to reduce the noise equivalent temperature difference to levels below 0.1K. The M-AERI includes two internal black-body targets for accurate real-time calibration. A scan mirror directs the field of view from the interferometer to either of the black-body calibration targets or to the environment from nadir to zenith. The mirror is programmed to step through a pre-selected range of angles. When the mirror is angled below the horizon the instrument measures the spectra of radiation emitted by the sea-surface, and when it is directed above the horizon it measures the radiation emitted by the atmosphere. The instrument was mounted under the flying bridge of the ship, on the port side, so that when pointed at the ocean surface the field of view was ahead of the ship's bow wave. The interferometer integrates measurements over about 2 minutes per view to obtain a satisfactory signal to noise ratio. It was programmed to view a sequence of angles covering the ocean and sky as well as the two calibration targets, and this cycle took about 20 minutes to complete. From these measurements it is possible to derive the oceanic skin temperature to absolute accuracies of ~0.1K and spectra of the infrared emissivity of sea water at the range of observation angles under the environmental conditions that prevailed during the cruise.

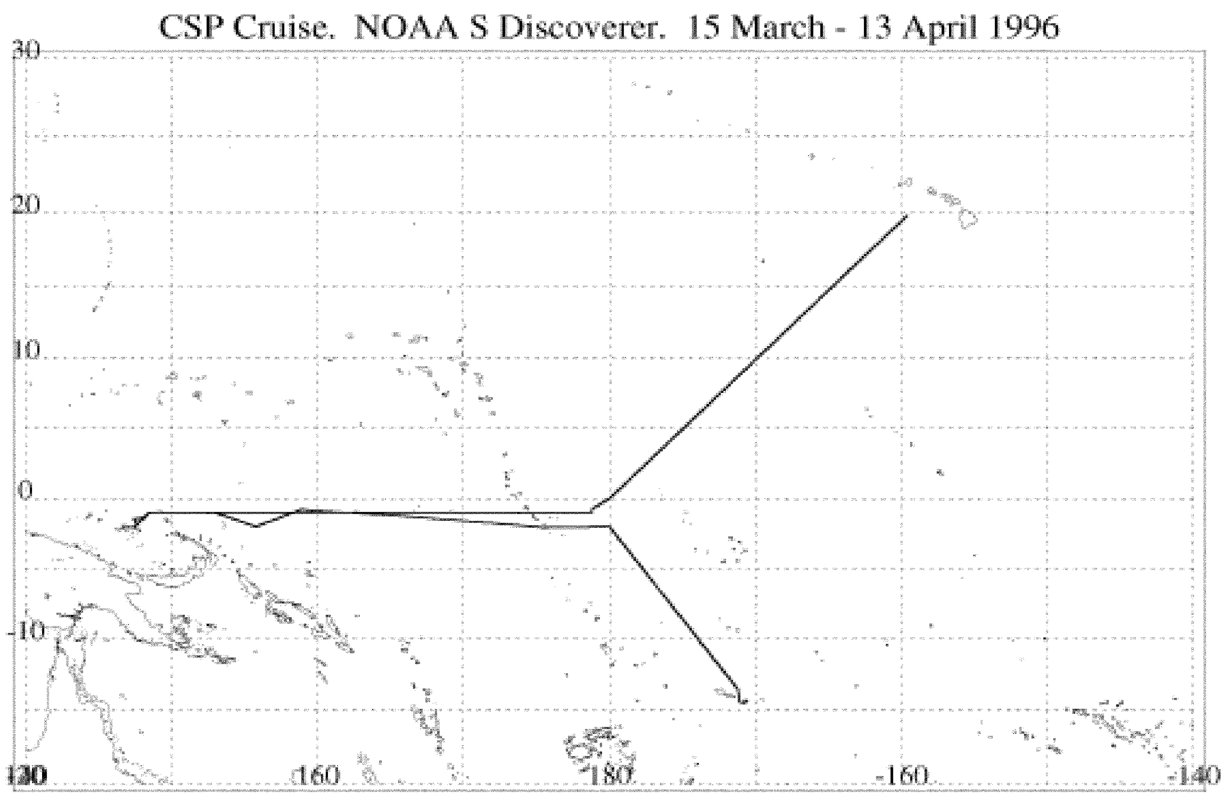

Figure 1. Trackline of the NOAA ship "Discoverer" during the Combined Sensor Cruise, March-April 1996. The cruise started in American Samoa, and followed a north-westerly line towards the Equator. Ten days were spent close to the island of Manus off Papua New Guinea. The cruise ended in Hawaii.

Other instruments deployed included two infrared thermometers (IRTs), that measured brightness temperatures in the infrared wavelength range of 9.6 to 11.5 µm. Although not capable of the high absolute accuracy of the M-AERI, the IRTs are able to make measurements with samples only seconds apart. Two were used during the cruise, one directed at the sea-surface, and the other at the sky. Their measurements will be analyzed to determine the effects of small-scale SST variability on the M-AERI measurements, and the consequences of changes in the sky radiation especially caused by clouds, a proportion of which is reflected into the M-AERI SST measurements. To monitor the cloud fields an all-sky camera was mounted on the ship with a time-lapse video recorder that stored images at ~17s intervals. The IRT data will also be analyzed to determine an optimum sampling strategy for the M-AERI validation of MODIS measurements.

While the ship was on station off Manus a surface-following float carrying a precision thermistor was deployed forward of the bow-wave to provide *in situ* measurements of the sea temperature at a depth of ~0.1m. Throughout the cruise a bulk temperature measurement from a depth of ~5m was provided by the ship's thermosalinograph system.

Other instruments on board, including a cloud radar, radar wind profiler, microwave radiometer, zenith-viewing FTIR, Raman lidars, aerosol samplers, broad-band short- and long-wave radiometers, turbulent flux probes and radiosondes, will provide a hitherto unsurpassed characterization the marine atmosphere. This will be very valuable in the interpretation of the M-AERI measurements.

The M-AERI began collecting data shortly after departure from Pago-Pago and continued to do so in a very reliable manner until the end of the cruise. The only data losses result from periods of rain showers, during which the instrument was covered by a tarpaulin, and occasional thermal-shocks that were associated with refilling the liquid nitrogen dewar.

The absolute accuracies of the M-AERI and of the NOAA zenith-viewing FTIR measurements were demonstrated by comparison of simultaneous spectra, taken from the zenith-viewing parts of the M-AERI measurement cycle, which showed agreement between the two sets of measurements, each with their independent calibration procedures, at the noise-levels of the instruments.

Comparison between the M-AERI derived skin SSTs show large differences caused by the skin effect, >0.5K (Figure 2), and diurnal effects, up to 2K (Figure 3). These are strongly dependent on environmental conditions, especially wind speed for the diurnal effects, and are larger than the anticipated uncertainties in the MODIS-derived SSTs. This underscores the need for using skin SSTs in the validation of the MODIS measurements, and of understanding the processes at the ocean-atmosphere interface that result in these temperature differences. Analysis of these data is continuing.

As a test of the MODIS infrared validation procedure, these data will be used to validate the infrared measurements from existing satellites, and data from the NOAA-12 and NOAA-14 AVHRR's, GOES-9 and GMS radiometers were collected for the duration of the cruise.

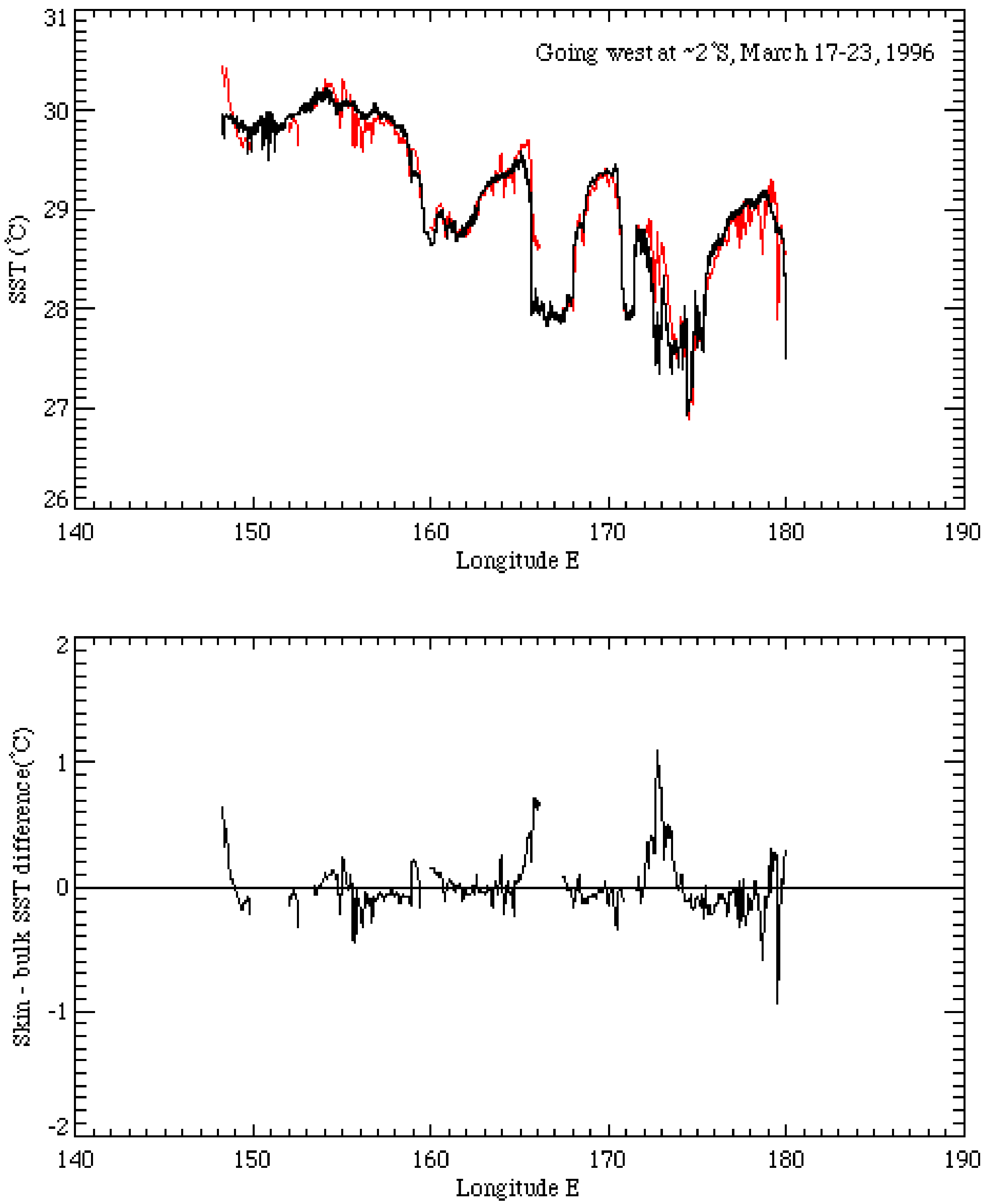

Figure 2. The skin temperature and bulk, *in situ* sea temperatures along the westward section at about 2°S. The *in situ* temperature is from a depth of 5m, and the skin temperature is a measurement taken at a wavelength of 10.5μm by the M-AERI, using an emission angle of 55°.

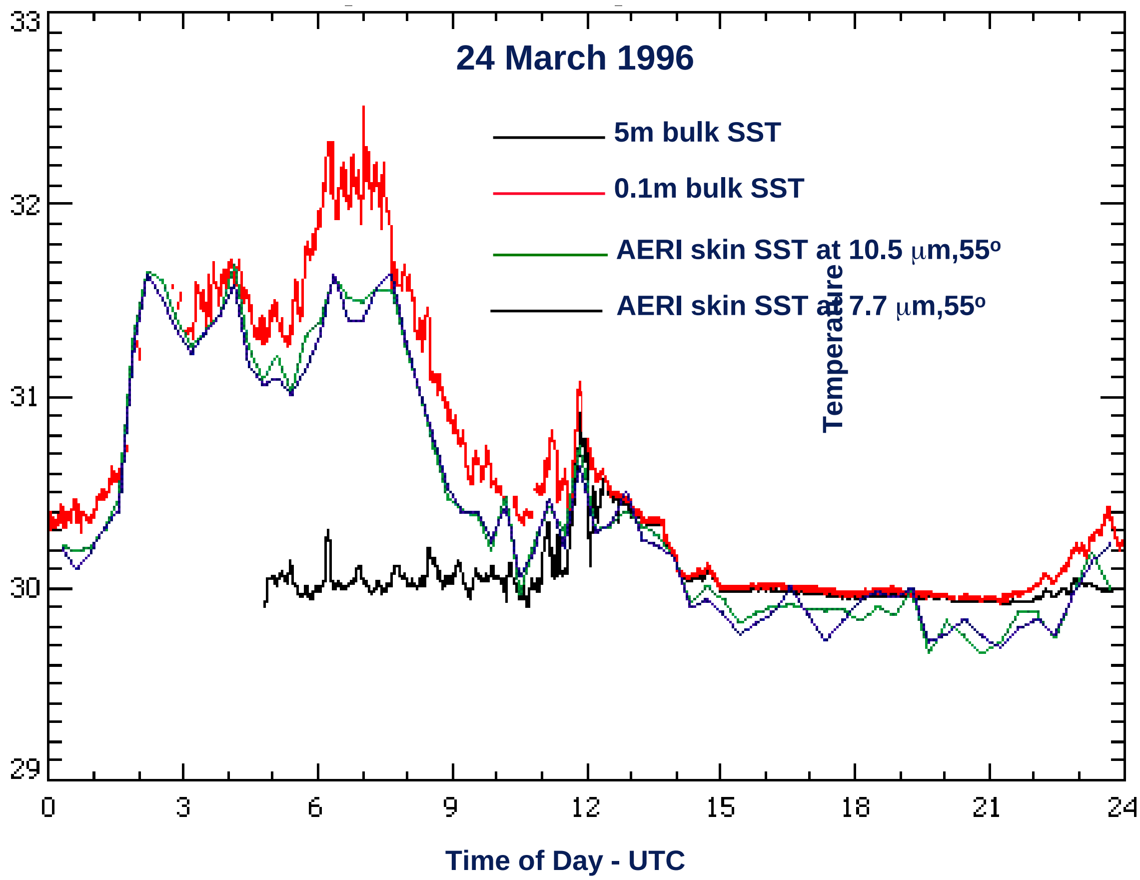

Figure 3. Measurements of a diurnal cycle of surface temperatures at a fixed station about 100km NE of Manus. Time is UTC, so to derive local sun time it is necessary to add ~10h. The wind was low and the sky largely cloud-free. These conditions are conducive to the formation of a large diurnal thermocline which is apparent in the 0.1m *in situ* temperature, but absent in the 5m *in situ* temperature. During the night when heat loss to the atmosphere drives convective mixing in the oceanic surface layer, the two *in situ* temperatures converge. Heat loss from the ocean throughout the period leads to a cool skin effect, as revealed by the M-AERI measurements. The two skin temperatures were measured at an emission angle of 55º, one at a wavelength of 7.7µm and the other at 10.5µm; the differences are believed due to the difference sensitivities of the measurements to reflected cloud radiance.

B.1.4 M-AERI improvements.

As a result of experience gained during the Combined Sensor Cruise, the need for a number of improvements to the M-AERI design became apparent. These include a cover over the zenith-view port, that would be closed during precipitation and thereby enable the continued acquisition of sea-surface spectra during rain. The liquid nitrogen dewar will be replaced by a Stirling cycle mechanical refrigerator of a similar design to those used to chill the detectors of spacecraft infrared radiometers. The motion of the ship will be monitored and recorded by using tilt-meters and accelerometers mounted on the FTIR optical bench, and a Global Positioning System receiver will be incorporated to provide accurate time and position of each measurement. A more flexible mounting system is required that will permit the easy deployment of the instrument on a range of ships or other platforms, and more modular construction of the control electronics is desirable. Improvements to the cabling linking the instrument to the control computer are needed.

A better user interface at the control computer is also desirable. These are currently being worked on at SSEC and a Design Review will be held there in late July. Delivery of the first instrument is expected in the fourth quarter of this year, and an acceptance cruise is planned in the neighborhood of Miami.

B.1.5 Arctic M-AERI deployment opportunity.

In early June there was an international workshop in Montreal to coordinate research efforts directed at understanding the physics and biogeochemistry of the North Water, a large polynya at the north of Baffin Bay. There are plans for a Canadian ice-breaking research vessel to spend three months in the area in the spring and summer of 1998, with a shorter cruise in 1997, and possibly a research cruise on a US vessel in 1999. Dr. Peter Minnett attended the workshop (supported by DOE funds) and was offered berths on the Canadian vessel, to measure the surface heat and radiation budgets of the polynya. Although the planned cruise will just precede the EOS-AM launch date, it will provide the opportunity to test the M-AERI in the Arctic, where the atmospheric conditions and surface temperatures are at the opposite climatological extreme to those in the Tropical Western Pacific. This cruise would be a pre-cursor to a high-latitude MODIS validation exercise to be carried out post-launch (details yet to be worked out).

B.1.6 Collaboration with ASTER infrared group

Dr. Peter Minnett attended the ASTER Science Team meeting in Pasadena, June 11-14, at which he gave three presentations (plenary, atmospheric correction working group and oceanography working group) on the MODIS infrared validation plans and areas of possible collaboration between the MODIS and ASTER groups. Because of the narrow swath width (60km) and limited duty cycle (~8%), it will be very difficult to use surface-based or aircraft measurements to build a sufficiently large data-base to validate the ASTER infrared measurements. An alternative approach will be to use the MODIS infrared measurements to validate the ASTER data (although the differences in the channel response functions of the two instruments will render it difficult to make direct comparison of measured brightness temperatures). ASTER, with 90m infrared pixels, will be able to contribute information on sub-pixel scale effects, such as unresolved clouds and SST variability on the MODIS infrared validation procedures.

B.1.7 Wide Area Networking

ATM networks have not been modified since the last report but are functioning well.

B.1.8 Documentation

A validation plan was submitted to the MODIS Project for infrared radiances (MODIS - Infrared Sea Surface Temperature Algorithm Science Data Validation Plan, O. Brown & P. Minnett. Submitted to NASA/GSFC, January 1996)**.** The strategy includes a combination of drifting buoy, cruise and fixed (time series) observations. It must be noted that this plan can only be carried out if the current out year support profile for this contract is sustained.

This document sets out the validation strategy for the MODIS infrared channels that are to be used in the derivation of SST. It proposes a multi-pronged approach using a variety of instruments and techniques that will provide quantitative bases for confidence in both the in-flight calibration procedure and the correction for atmospheric effects in the SST determination.

This document will be revised at appropriate intervals to take into account new findings in this field, and to document new collaborative opportunities that may be relevant to the MODIS AM-1 infrared validation exercise.

C. Investigator Support

January	none	**April**	V. Halliwell
February	none	**May**	V. Halliwell P. Minnett
March	V. Halliwell	**June**	W. Baringer O. Brown P. Evans V. Halliwell P. Minnett

D. Future Activities

D.1 Current:

D.1.1 Algorithms

a. Continue to develop and test algorithms on global retrievals
b. Evaluation of global data assimilation statistics for SST fields
c. Continue radiative transfer modeling using RAL code
d. Participate in Combined Sensor Cruise, and analyze data
e. Continue to study near-surface temperature gradients
f. ATBD updates (as needed)
g. Validation Plan updates (as needed)
h. EOS Science Plan updates (as needed)
i. Define and implement an extended ATM based network test bed
j. Evaluate and analyze results of calibration/validation experiment
k. Continued integration of new workstations into algorithm development environment
l. Continued participation in MODIS Team activities such as the MOCEAN meeting in July 1996.

D.1.2 Investigator support

Continue current efforts

E. Problems

No new problems to report.

F. Publications

None to report.